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NONLINEAR ACOUSTICS FOR HEALTH MONITORING OF COMPOSITE PATCH REPAIRS

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Abstract

The paper investigates the problem of structural health monitoring of composite patch repairs used in aerospace applications. Two diagnostic techniques are applied to evaluate the structural health of two carbon fiber reinforced composite samples with bonded patch repairs; one test sample has a correctly manufactured patch repair without manufacturing defects while the second sample has a patch repair with multiple simulated debondings. Firstly, the classical ultrasonic c-scan is performed to confirm the assumed initial state of both samples i.e. exclude the presence of manufacturing defects in the first sample and to confirm the presence and location of the debondings in the second sample. Secondly, the non-classical nonlinear ultrasonic technique - based on vibro-acoustic wave modulations - is applied to verify its usefulness in testing of complex structural components. The paper gives technical details of the test samples and measurement techniques. Diagnostic procedures and results are presented and discussed.

1 Introduction

Aerospace industry moves towards the implementation of larger volume of advanced composite materials in the new age commercial aircrafts [1,2]. Until recently the composites were used in aircraft industry mainly for the secondary structure (e.g. winglets or trailing edge panels) or interiors of aircraft (e.g. sidewalls, ceiling panels or partition walls). Nowadays, the composites are being used also in the primary structure of aircraft (e.g. fuselage skin, engine fan blades or outer wing box). The primary structure, responsible for load bearing, is critical for the performance and safety of aircraft. For this reason Non-Destructive Testing (NDT) and Structural Health Monitoring (SHM) of composite structures become important in aircraft design and maintenance [3-4]. It is well known that one of the main drawbacks of composite materials is their susceptibility to impact damage. The most common type of damage results from a blunt force impact. In aerospace applications this type of impact damage usually is a consequence of collision with ground service equipment, bird strike, hail impact or runaway debris during take-off or landing. Replacement of damaged areas is not a preferable solution due to the high level of integration and the big size of components. Therefore there is an increasing interest in various repair technologies performed on primary structural components of aircraft. The use of adhesively bonded composite repair patches is one of the possible solutions. Bonded patch repair technologies provide an alternative solution to mechanically fastened repairs with significantly higher performance [5-7].

The paper demonstrates the application of nonlinear ultrasonic technique - based on vibro-acoustic wave modulations - for quality inspection and monitoring of bonded repairs, demonstrating its great potential for aerospace applications.

2 Description of test samples

The test samples investigated were two carbon fiber reinforced composite coupons with bonded patch repairs, as shown in Fig. 1. The analysed composite substrate consists of 5 plies with theoretical thickness of 1.6 mm and ply orientation of [0/90°/0/90°/0]. Repair patches were applied on the substrate coupons in a manual way after surface preparation with sand paper and cleaning with degreasing agent. The repair patches were composed of five plies of *HEXCEL 43280* reinforcement impregnated with *Epocast 52 A/B* epoxy resin. Impregnation was performed on a heated table surface (60°C) in order to obtain low viscosity of the resin. The repair patch plies were placed on the substrate with the ply orientation of [0/90°/0/90°/0°]. After the five-ply lay-up completed, curing was performed for 4 hours in 95°C in oven under vacuum conditions (- 700 mbar pressure).

Two test configurations were considered for the present study as shown in Fig. 1.

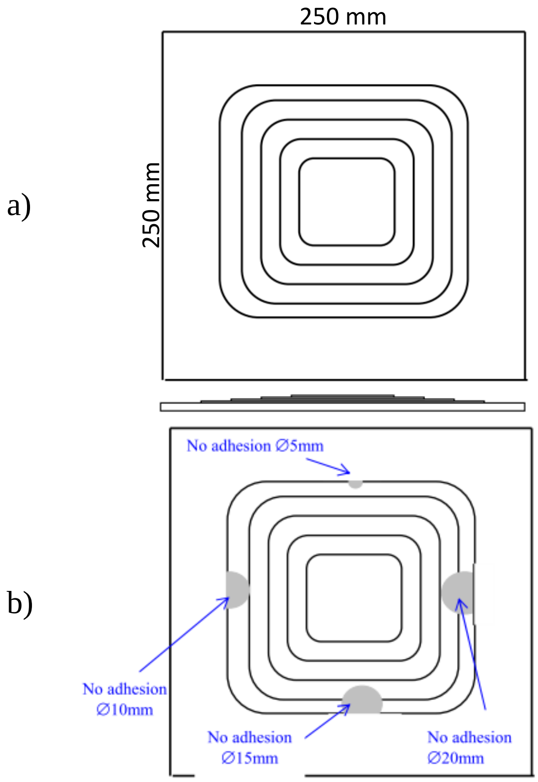

Fig. 1. Geometry of the test samples: (a) patch repair without defects; (b) patch repair with four regions of “no adhesion” between the lowest ply of the repair patch and the substrate.

Configuration 1 was an undamaged case, where the five plies of the repair patch were properly impregnated on the substrate. *Configuration 2* was a damaged case, where the five plies of the repair patch were impregnated on the substrate with 4 areas of “no adhesion” between the substrate and the first impregnated ply. The “no adhesion” condition was seeded by inserting locally a Teflon film cut to the defined locations.

3 Ultrasonic C-Scanning

Nondestructive testing by ultrasonic C-Scan method was performed on both samples after the manufacturing of the patch repairs. The goal of this NDT inspection was to confirm the assumed initial state of both samples i.e. to exclude the presence of manufacturing defects in the first sample and to confirm the presence and location of the debondings in the second sample. An ultrasonic transducer working at the 5 MHz central frequency was used. The test was performed in the pulse-echo mode. The samples were scanned with the spatial resolution of 0.5 mm. Results of the inspection are shown in Fig. 2. The results show that the C-Scan image of the undamaged sample (Fig. 2a) does not contain any localized features indicating improper bonding between the repair patch plies and the substrate. In contrast, the C-Scan image of the damaged specimen exhibits the areas with “no adhesion” between the repair patch and the substrate. These areas can be seen in Fig. 2b as bright spots on at the locations of Teflon inserts.

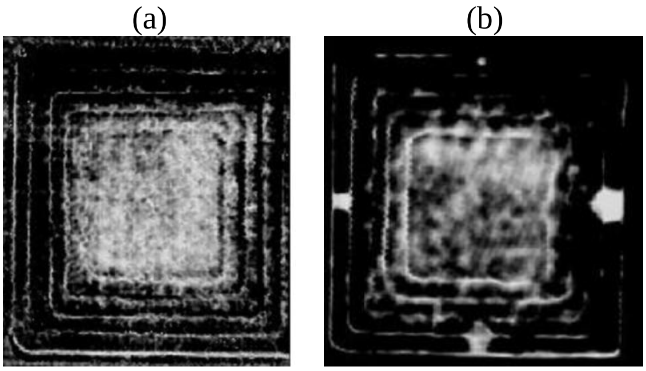

Fig. 2. Result of the ultrasonic C-Scan testing for (a) the undamaged sample and (b) the damaged sample. The areas with no adhesion between the repair patch and the substrate are visible as bright spots on image (b).

3 Nonlinear vibro-acoustic modulations used for damage detection

The second inspection method considered in this study is based on a combined vibro-acoustic modulation of a strong intensive low-frequency (modal) vibration by a weaker high-frequency (ultrasonic) wave. These two excitations are introduced to the structure simultaneously, as illustrated in Figure 3. The technique is often referred to as the vibro-acoustic modulation technique (VAM) [8-11] or the nonlinear wave modulation spectroscopy (NWMS) [12].

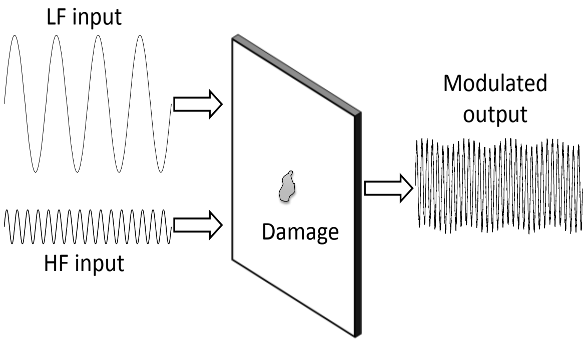

Fig. 3. The principle of vibro–acoustic nonlinear modulation

When the combined vibro-acoustic excitation is applied to a monitored structure - and a linear behavior of material in the low strain regime is assumed (as in the case of strains associated with ultrasonic wave propagation) – two possible ultrasonic responses are possible. Firstly, when the investigated structure is undamaged, the spectrum of the measured vibration response signal exhibits only the major frequency components, i.e. the propagating high-frequency (HF) acoustical wave and the low-frequency (LF) excitation, as illustrated in Fig. 4a. Secondly, when the investigated structure is damaged, the spectrum of the response signal reveals additional components, i.e. higher harmonics and modulation sidebands around the HF component, as shown in Fig. 4b. The LF excitation is commonly referred to as the pump frequency, while the HF excitation is referred to as the probe frequency. Various experimental procedures and excitation methods have been used in this area of research.

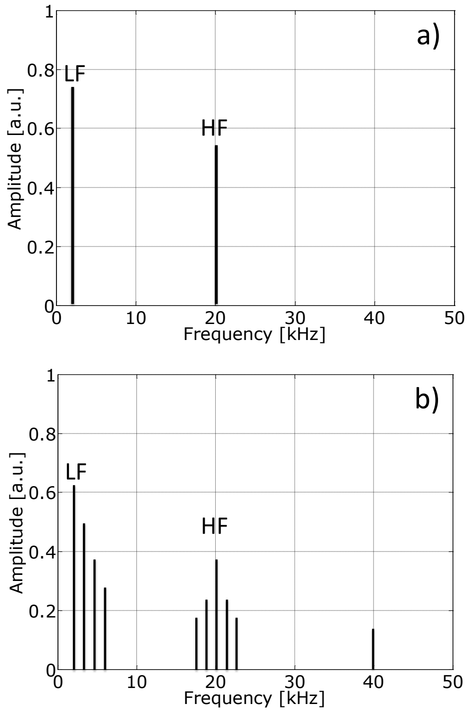

Fig. 4. Response spectra in nonlinear vibro-acoustic tests for: (a) undamaged component; (b) damaged component.

The parameter that is frequently used as an indicator of damage is the coefficient R that describes the intensity of modulation and can be defined as

$$R = \frac{(A_{LSB}^{1} + A_{RSB}^{1})}{A_{HF}} \qquad (1)$$

where A_{HF} is the spectral amplitude of the carrier (acoustical) frequency, A_{LSB}^{1} and A_{RSB}^{1} are the spectral amplitudes of the first pair of modulation sidebands (i.e. spectral components corresponding the HF±LF frequencies). The LF excitation is frequently selected to coincide with on of the structural resonances of the test sample in order to increase the level of strains generated in the sample for a given input power. The HF excitation is selected arbitrarily in the range from a few kHz to few hundred kHz.

3 Nonlinear vibro-acoustic modulation tests

Experimental modal analysis was performed initially in order to find structural resonances of the test samples. The same measurement set-up was used for both samples. The plate was freely suspended using elastic cords to obtain the free-free boundary conditions. The surface-bonded *Noliac CMAP4* stack actuator was used to excite the component. The white noise excitation signal was generated by a built-in *Polytec* signal generator and amplified by an *EC Test Systems PAQG* amplifier. A *Polytec PSV-400* Scanning Laser Doppler vibrometer (SLDV) was used to acquire vibration responses. The Frequency Response Functions (FRFs) were calculated from the experimental input and output data using the *Polytec PSV* software. FRF amplitudes were gathered from the 27×27 measurement grids to obtain the relevant mode shapes corresponding to the selected natural frequencies. The experimental set-up used is shown schematically in Fig. 5.

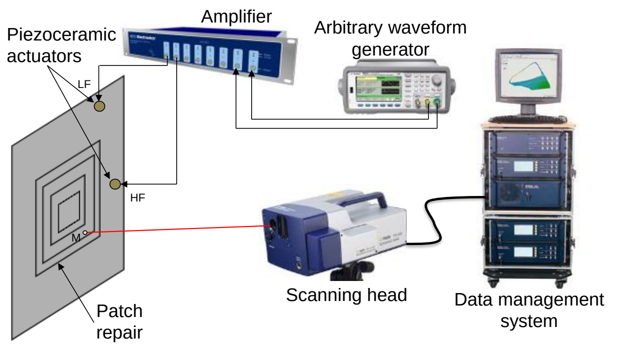

Fig. 5. Experimental set-up used for the modal analysis and for the nonlinear vibro-acoustic modulation tests.

After performing the modal analysis tests the frequency of the first structural resonance of the sample was chosen for the LF pump excitation in all nonlinear VAM tests. This resonant frequency was identified as 261 Hz for the undamaged sample and 258 Hz for the damaged sample. Fig. 6 gives the corresponding mode shape. The shift in resonant frequencies between the damaged and undamaged samples is possibly due to stiffness reduction in the areas of "no adhesion" between the repair patch and the substrate. However, due to the fact that only two specimens were tested, it is also possible that the observed frequency differences result form the inherent variability of the composites samples.

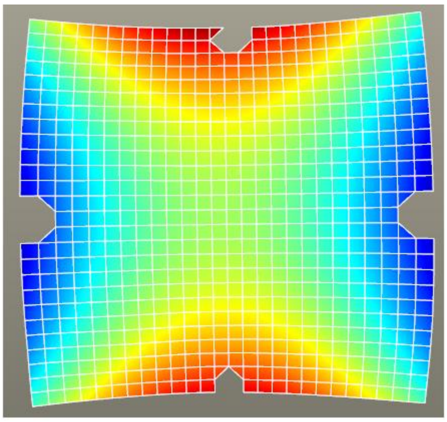

Fig. 6. Mode shape of the first structural resonance.

In all nonlinear VAM tests the experimental set-up described above was supplemented with an additional small piezoceramic stack actuator for high frequency ultrasonic excitation. The frequency of HF excitation was equal to 45 kHz, and the amplitude of driving voltage was equal 80 Vp-p. The driving voltage for the LF pump excitation was incrementally increased from 10 to 70 Vp-p in 10 Vp-p steps. The modulation spectra for each LF voltage were acquired at six different points on the test sample. Subsequently the modulation intensity coefficients were computed for each point using Eq. 1.

Fig. 7 presents the dependence of the LF amplitude on driving voltage for the undamaged (solid line) and damaged (dotted line) components. These curves combine average responses for all six measurement locations. The results show that the amplitude of LF signal increases with the increasing driving voltage., as expected. However, the slope of this increase is significantly steeper for the damaged component. Moreover the results also sow that for the damaged sample response amplitudes are noticeably lower than for the undamaged sample. It is possible that this amplitude decrease (or in other words damping increase) together with the observed resonance frequency shift could be also an indicator of the presence of damage in the analyzed components. However this needs further investigations.

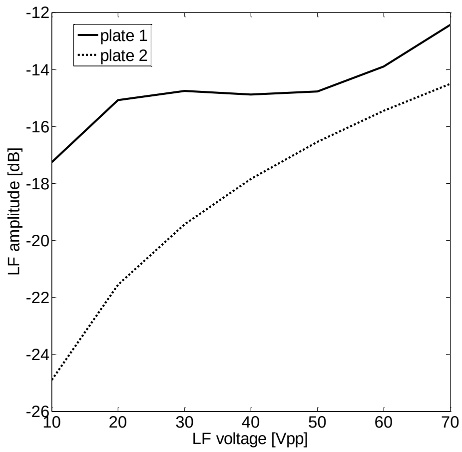

Fig. 7. Dependence of the LF amplitude on the applied driving voltage for the undamaged (solid line) and damaged (dotted line) samples.

Fig. 8 presents the dependence of the HF amplitude on the applied LF driving voltage for the undamaged (solid line) and damaged (dotted line) samples. These curves are the average response amplitudes for all six measurement points.

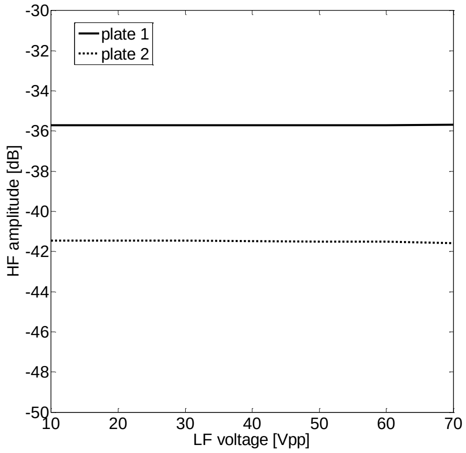

Fig. 8. Dependence of the HF amplitude on the applied LF driving voltage for the undamaged (solid line) and damaged (dotted line) samples.

The results do not reveal any dependence of the HF amplitude on the LF driving voltage. Similarly, to the LF amplitudes, also in this case the amplitudes of HF signal for the damaged sample are noticeably lower.

Finally, the modulation intensity coefficients for both samples were compared. The results are presented in Fig. 9. The results demonstrate that there is a difference between the two samples investigated. Nonlinear modulation intensity increases significantly with the LF amplitude for the damaged component - if compared with the undamaged component - indicating strong nonlinearity resulting from disbonded repair patches. It is also important to note that the intensity of nonlinear modulations increases monotonically with the amplitude of the applied low frequency excitation (i.e. with the increasing level of strains in the sample).

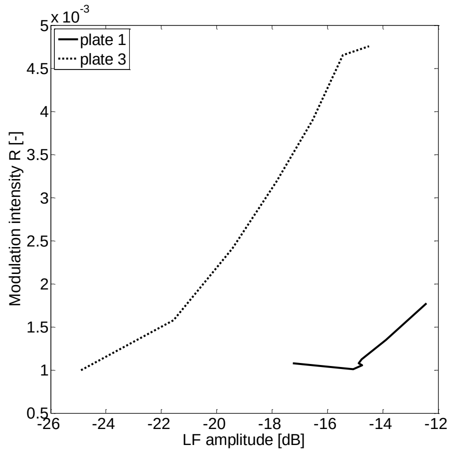

Fig. 9. Dependence of the modulation intensity coefficient R on the amplitude of LF excitation. Solid line represents the undamaged sample and dotted line represents the damaged sample.

4 Summary and conclusions

The nonlinear VAM technique has been used for detection of disbonds in composite repair patches. The method has utilized piezo-based LF vibration and HF ultrasonic excitations. The work presented has been focused on the analysis of modulation intensity.

The results demonstrate that the analysis of nonlinear modulation intensity can be used to discriminate between the undamaged and damaged scenarios. However, it is important to note that the nonlinear VAM technique offers so far only the first level of damage identification, i.e. the capability to detect the presence of damage. Nevertheless the method requires a relatively simple experimental set-up and can be implemented using low-profile and built-in piezoceramic transducers, allowing for on-line monitoring in SHM applications.

Further work in this area is underway to achieve identification of damage location and to test the technique in real industrial environment. More research work is also needed to understand physical mechanisms behind observed signal modulations that could lead to identification of different types of damage.

Acknowledgments

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